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Theoretical Investigation of The Dynamical and Static Characteristics of Vertical-Cavity Surface-Emitting Lasers Incorporating Two-Dimensional Photonic Crystals

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ABSTRACT

In this work we present a spatial and dynamical model of a semiconductor vertical-cavity surface-emitting laser (VCSEL) incorporating a spatial built-in optical waveguide created by the defect in a two-dimensional photonic crystal (PC). The PC is created by an array of air-holes etched in to the VCSEL. Results of investigations of power versus current and dynamical characteristics of a conventional proton-implanted VCSEL and VCSELs incorporating PC defect waveguides operating with effective index and photonic band-gap guidances are presented and discussed. Results show that the VCSELs with incorporated PCs between laser mirrors provide a dramatic decrease of the power of the fundamental laser mode. Application of multiple-defect photonic band-gap (PBG) waveguides provides an additional dominance of the fundamental mode, and thus, the PC creates high-power but single-mode radiation of VCSELs which is impossible in conventional VCSELs.

Keywords: vertical-cavity surface-emitting lasers, photonic crystal, photonic band-gap, single-mode, high-power.

1. INTRODUCTION

Vertical-cavity surface emitting lasers (VCSEL) are one of the dominant optical sources for local optical telecommunication networks [1]. They consist of an active region normally containing quantum-wells situated between two distributed Bragg reflectors (DBR). There are two commonly used methods for current confinement involving a proton implant or an oxide. Such lasers are known as proton-implanted and oxide-confined VCSELs. In VCSELs of first type, the proton-implant creates a guiding channel for injected carriers due to the high resistance of the proton implant region. The proton implant and the oxide limit carrier flow and establish gain-guided regime. In oxide-confined VCSELs, the oxide also creates a gain-guided waveguide, but these VCSELs have an additional optical confinement provided by the oxide because the oxide has smaller refractive index in comparison with surrounding semiconductor.

The optical modes of the VCSEL are unusually separated into longitudinal and transverse modes. While wavelength spacing between longitudinal modes is large, the spacing between transverse modes is small, which leads to the competition between the modes and a change of shape of the laser beam. These effects are undesirable for most applications [2]. The transverse mode spacing is affected by the nature of the optical confinement in VCSELs. Recently, it was proposed to introduce a photonic crystal (PC) defect waveguide within the VCSEL to control the transverse optical modes [3]. This waveguide is created by removing one air hole from the array of air-holes made in semiconductor. This structure can provide single-mode guidance at extremely large core radii of this PC waveguide – 10 or even 20 microns [4]. Typically, single-mode VCSELs have 4 – 5 micron oxide or proton implant aperture diameter. That is why we wish to apply the presented PC waveguide in order to create single-mode conditions for large beam apertures, and thus, increase the power of the radiation. In that case, the control of the transverse electrical current is provided by the proton implant or oxide and the optical wave control is given by the PC waveguide.

In this paper, the results of investigations of effects limiting the single-mode operation of VCSELs with PC deposited between mirrors shall be considered theoretically. Selected results describe power versus current characteristics of the VCSELs and the dynamical responses of the VCSELs.

2. DESCRIPTION OF THE THEORETICAL MODEL AND INVESTIGATED VCSELs

We have merged the previously developed optical model [5] with the spatial and temporal model of a VCSEL [6]. The model includes the transverse carrier diffusion equation, the rate equations for photon density in each optical mode, the scalar Helmholtz equation and the equation of thermal diffusion. This model takes into account the two-dimensional distribution of electrical field of modes taking place in a VCSEL. The VCSEL model describes the radial distribution of the carrier density and can treat an infinite number of modes, but we limit our consideration to two first modes in frame of this work. The key feature of the optical model here is the transverse refractive index distribution including influences of carrier injection, temperature, gain and air-holes defining the PC.

The investigated theoretical structure of the VCSEL consists of a quantum-well active layer deposited between two distributed Bragg reflectors as shown in Fig. 1. Injected current is confined by the proton-implanted region of radius r_a . The main parameters of the VCSEL are presented in Table 1. Four kinds of VCSELs are considered:

Case 1. A conventional VCSEL without a PC;

Case 2. A VCSEL with an effective-index single-mode waveguide created by the defect in the PC [5]. The defect is created by removing one air hole from the array of air-holes defining the PC. In the PC, the air-hole diameter is $d = 0.3333$ micron, the centre-to-centre spacing is $A = 1$ micron;

Case 3. A VCSEL with a waveguide created by the PBG PC defect waveguide. The defect is created by removing one air hole, parameters of the PBG PC are defined using MBP software [7]. $d = 0.234$ micron, $A = 0.39$ micron;

Case 4. A VCSEL with a waveguide created by the photonic band-gap waveguide with multiple defects. $d = 0.234$ micron, $A = 0.39$ micron.

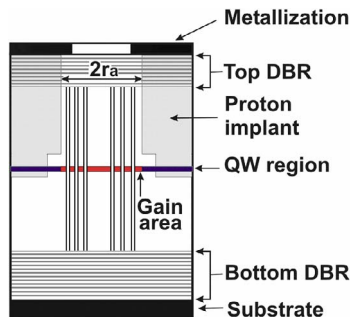


Figure 1. Schematic presentation of the proton-implanted VCSEL. Vertical cylinders along the laser resonator represent air-holes creating the PC.

Table 1. Basic parameters of the VCSEL.

Vacuum wavelength	790 nm
Carrier density at transparency	$1.5 \times 10^{24} \text{ 1/m}^3$
Differential gain constant	$5.2 \times 10^{-20} \text{ m}^2$
Gain suppression factor	$3 \times 10^{-23} \text{ m}^3$
Carrier lifetime in active later	2 ns
Effective reflectivity of top DBR for LP_{01} mode	0.99
Effective reflectivity of bottom DBR for LP_{01} mode	0.997
Effective reflectivity of top DBR for LP_{11} mode	0.99
Effective reflectivity of bottom DBR for LP_{11} mode	0.999
Refractive index of the passive GaAs active layer	3.6
Radius of proton-implanted region	3 microns
Radius of the VCSEL chip	8 microns
Number of GaAs/AlGaAs pairs in top DBR	24
Number of GaAs/AlGaAs pairs in bottom DBR	32.5
Distance between DBRs and the active zone	110 nm

3. RESULTS OF SIMULATIONS

3.1 Power versus current characteristic

Powers versus current characteristics of the presented VCSELs assuming that the PC is situated between two unetched DBRs of VCSEL are shown in Fig. 2. The conventional VCSEL (case 1) has two modes and LP_{11} mode appears at currents above 4 mA taking some power from the fundamental LP_{01} mode. The incorporation of a PC radically changes laser characteristics. The intensity of the fundamental LP_{01} mode is fixed in a wide range of injected currents while the intensity of LP_{11} mode grows resulting in a rise of the total power of the VCSEL. In the case 2 the PC decreases the power of the fundamental mode and transfers more power into high-power modes of the VCSEL. These modes are defined and confined by the wide built-in waveguide of the VCSEL due to the change of the refractive index with temperature and carrier density. VCSELs corresponding to case 3 look more attractive, because the PC establishes nearly single-mode without a significant increase of the output power of the VCSEL. In the case 4 the PC waveguide increases the power of VCSEL proportionally to the number of defects and the power of the second-order mode is very small across whole range of investigated electrical currents. The increase of the optical power due to the application of the PBG PC defect waveguide is explained by better transverse confinement of modes in defects of these PCs comparing to the effective-index PC waveguides and built-in waveguides of conventional VCSELs. Rapid jumps of power versus current are explained by the independent acting of each resonant defect in the PC PBG waveguide.

3.2 Dynamical characteristics

The main area of VCSEL applications is in optical telecommunication networks; therefore, let us estimate the speed properties of the switch-on dynamics of these VCSELs presented in Fig. 3 assuming that the PC waveguide is fabricated between DBRs which is now achievable [8]. These dynamical responses show that the case 2 provides the increases the amplitude of high-frequency oscillations of the radiated power of both modes of the VCSEL after the switch-on. Therefore, this VCSEL could have better modulation properties at high modulation frequencies compared to the conventional VCSEL. The PBG single-defect waveguide fabricated in

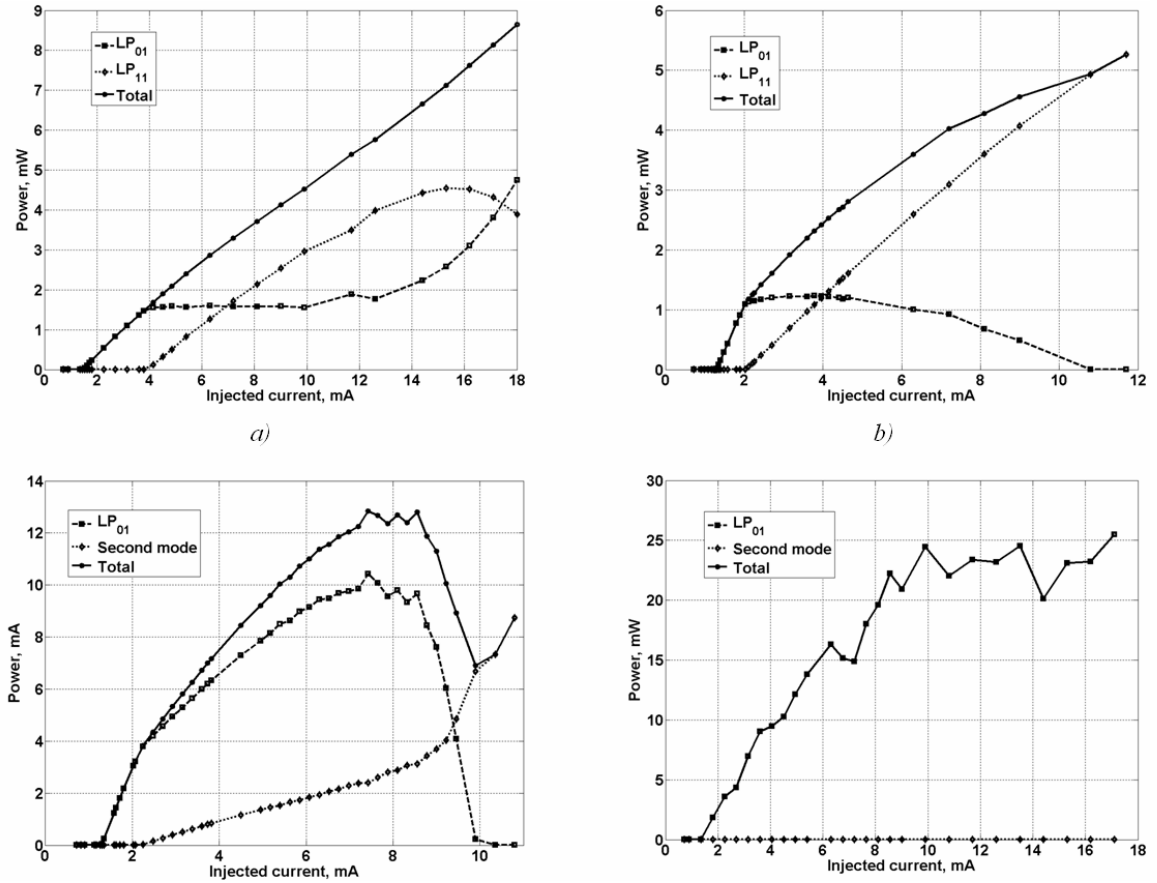


Figure 2. Power versus current characteristics of the (a) conventional VCSEL, (b) the VCSEL with the effective-index PC waveguide, (c) the VCSEL with the single-defect PBG PC waveguide and (d) the VCSEL with the multiple-defect PBG PC waveguide.

the VCSEL reduces both the decay time and the amplitude of oscillations by a factor of two and, this laser could be more promising than the cases 1 or 2. The VCSEL of case 4 has a very low intensity for the second-order mode, and the intensity of the fundamental mode is high. The dynamical characteristic of LP_{01} mode has a lot of peaks which appear to be due to the independent operation of each of the PBG PC defects in the VCSEL. This VCSEL will have worthier modulation properties compared to the VCSEL with the single-defect PBG PC waveguide.

Fig. 4 shows the dynamical evolution of the LP_{01} mode wavelength in the investigated VCSELs. This characteristic shows that the fabrication of a PC does not change the dynamical properties of the wavelength, but the fabricated PC shifts mode wavelengths and spectra to the short-wavelength region. This shift is larger for the PBG PC because in the PBG PC waves propagate more into air-holes compared to effective-index PC.

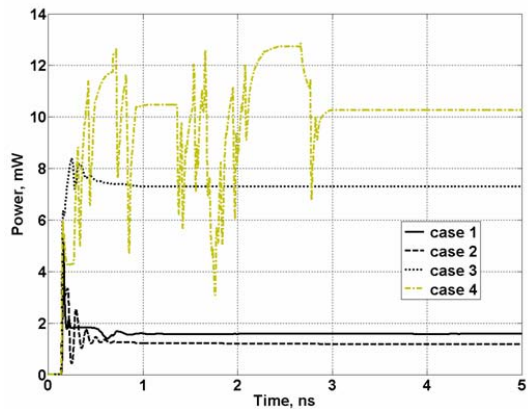


Figure 3. The switching-on power dynamics of LP_{01} mode of the investigated VCSELs at injected current of 4.5 mA ($\sim 3I_{th}$).

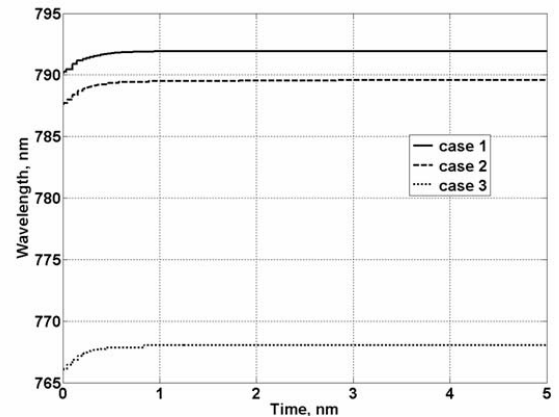


Figure 4. The switching-on dynamics of LP_{01} mode wavelength at injected current of 4.5 mA ($\sim 3I_{th}$) of the investigated VCSELs.

4. CONCLUSIONS

In this work novel VCSELs incorporating single- and multiple-defect effective-index and PBG PC between two DBRs of VCSELs were considered theoretically. The application of the single-mode effective-index PC waveguide to the definition of single-mode conditions is not justified. The effective-index waveguide creates a lower index contrast compared to the built-in waveguide in VCSEL defined by temperature and carrier profiles. Thus, the optical modes are more defined by the built-in waveguide rather than by PC. Beside this, the waveguide decreases oscillations of the dynamical characteristic and improves speed properties of the VCSEL slightly.

The most interesting results were obtained with photonic band-gap defect PC waveguides embedded in the VCSELs between DBRs. The single-defect waveguide suppresses high-order modes, increasing the intensity of the fundamental mode and the total power of the VCSEL radiation. The dynamical properties of such VCSELs are also better compared to the conventional VCSELs where the decay time of oscillations is almost 2 times larger than in PBG PC VCSELs. VCSELs with multiple-defect PBG PC waveguides have demonstrated the higher optical power of the fundamental mode mainly due to the better utilization of carriers into the mode across the transverse plane of the VCSEL. The intensity of the second-order mode is negligibly small. These VCSELs have better dynamical properties resulting in a decay time 3 times smaller than the time in the conventional VCSEL without a PC. These defects act separately, therefore, in practice their geometrical characteristics and resonant wavelengths would be different. It will lead to an additional noise in the frequency domain of the complex fundamental mode composed by fundamental modes of each defect.

A blue shift of the mode wavelengths and spectra is observed in VCSELs with PCs, this shift is larger for PBG PC and it can be used to tailor the VCSEL spectra.

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